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THE CALCULATED EFFECT OF VARIOUS HYDRODYNAMIC AND
AERODYNAMIC FACTORS ON THE TAKE-OFF OF A LARGE FLYING BOAT

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SUMMARY

An investigation was made of the influence of various factors and design parameters on the take-off performance of a hypothetical large flying boat by means of take-off calculations. The parameters varied in the calculations were size of hull (load coefficient), wing setting, trim, deflection of flap, wing loading, aspect ratio, and parasite drag.

The take-off times and distances were calculated to the stalling speeds and the performance above these speeds was studied separately to determine piloting technique for optimum take-off. The advantage of quick deflection of the flap at high water speeds is shown.

INTRODUCTION

Present designs for large flying boats are characterized by high wing loading, high aspect ratio, and low parasite drag. The high wing loadings result in the universal use of flaps for reducing the take-off and landing speeds. These factors have an effect on take-off performance and influence to a certain extent the design of the hull.

The purpose of the investigation described in this paper is to evaluate the importance of various design parameters that influence the take-off performance of a large hypothetical flying boat representative of present design practice. Some of the parameters have been studied in earlier investigations but not in connection with aerodynamic and hydrodynamic characteristics now of interest such as low-area high-aspect-ratio wings, low parasite drag, high length-beam ratio for the hull, and high loadings of the hull.

PROCEDURE AND CALCULATIONS

The parameters studied in the investigation are as follows:

1. Size of hull (load coefficient).
2. Wing setting.
3. Trim.
4. Deflection of flap.
5. Wing loading.
6. Aspect ratio.
7. Parasite drag.

The effect of variation in these parameters on net accelerating force and take-off performance was calculated for a hypothetical flying boat having the following basic characteristics:

Gross load, lb.	100,000
Wing	
Root section	N.A.C.A. 23018
Tip section	N.A.C.A. 23009
Taper ratio	0.333
Total horsepower at take-off (4 engines)	6,000
Propeller	
Diameter, ft.	14
Number of blades	3
Type	Constant speed
Flaps	
Span, percent wing span	0.60
Chord, percent wing chord	0.20

Flaps (cont'd.)

Type

Simple, split

Location

Half on each side of center line of flying boat

The form of the hull was assumed to be similar to that of a model tested in the N.A.C.A. tank for which general test data as yet unpublished were available. This model has a transverse step, pointed afterbody, and length-beam ratio excluding tail extension of 5.5. The lines are considered to be representative of current practice for large flying boats.

The lift and drag coefficients of the wing without flaps were obtained from variable-density-tunnel data, and the method of reference 1 was used in calculating the lift and drag coefficients for wings with 15° and 30° flap deflection. Ground effect was calculated by conventional methods (reference 2), and was included in computing the effective aspect ratios. The resulting lift and drag curves are shown in figures 1 and 2. The drag curves include the profile drag of the wing. Thrust data for the assumed propeller were obtained from propeller-research-tunnel tests.

The hull was assumed to be free-to-trim up to a speed below the hump speed where the trim became that for minimum water resistance. Above this speed the trim was assumed to be that for minimum water resistance, except where specified otherwise.

The total resistance and the take-off performance were calculated by the methods described in reference 3. The times and distances were in all cases calculated only up to the stalling speed. Performance above the stall was treated separately in several cases to find the trims for least total resistance at these speeds and hence the proper procedure for "pull-offs" to obtain best over-all take-off performance. For those cases the graphical method for obtaining time and distance described in reference 4 was introduced to show graphically the effect of changes in accelerating force on time and distance.

The arbitrary variations in parameters assumed, the figure numbers for the plotted results, and the calculated variations in take-off performance are summarized in the following table.

SUMMARY OF CALCULATIONS

Parameter considered	ASSUMPTIONS							RESULTS			
	Load coefficient C_{L0}	Wing setting, deg. α_w	Parasite drag coef. excluding hull C_{Dp}	Wing loading, lb./sq.ft. W/S	Effective aspect ratio, A_e	Flap deflection, deg., δ_F	Departure from best trim, deg.	Figure no.	Time to stalling speed, sec.	Distance to stall- ing speed, ft.	Stalling speed, f.p.s.
Load coef- ficient with and without flaps	0.5 .78 1.10	5	0.01	25	20	0	0	3	50.4 51.5 60.4	3685 3500 3795	118
	.5 .78 1.10	5	.01	25	20	30	0	4	43.0 44.5 51.8	2775 2730 3025	104
Wing setting with and without flaps	.78	5 9	.01	25	20	0	0	6	51.5 46.6	3500 3055	118
	.78	5 9	.01	25	20	30	0	7	45.4 44.5	2810 2730	104
Departure from best trim, with and without flaps	.78	5	.01	25	20	0	0 $1\frac{1}{2}$ above 3 above $1\frac{1}{2}$ below 3 below 70 fixed trim	10	51.5 56.6 104.8 67.3 No take-off 63	3500 3795 6670 4610 No take-off 4900	118
	.78	5	.01	25	20	30	0 $1\frac{1}{2}$ above 3 above $1\frac{1}{2}$ below 3 below	11	44.7 48.5 72.2 52.9 No take-off	2740 2965 4455 3275 No take-off	104

	ASSUMPTIONS							RESULTS			
	Load coefficient C_{Δ_0}	Wing setting, deg. Γ_w	Parasite drag coef. excluding hull C_{Dp}	Wing loading lb./sq.ft. W/S	Effective aspect ratio, A_e	Flap deflection, deg., δ_F	Departure from best trim, deg.	Figure no.	Time to stalling speed, sec.	Distance to stall- ing speed, ft.	Stalling speed, f.p.s.
Flap de- flection at two wing loadings	0.78	5	0.01	25	20	0	0	15	51.5	3500	118
						15			45.1	2840	109
						30			45.4	2810	104
	.78	5	.01	35	20	0	0	16	89.7	7850	140
						15			77.6	6305	129
						30			76.8	6055	123
Aspect ratio at two wing settings	.78	5	.01	25	10.5	0	0	18	54.4	3780	118
					20				51.4	3485	
					30.5				49.2	3300	
	.78	9	.01	25	10.5	0	0	19	53.1	3615	118
					20				46.6	3055	
					30.5				45.5	2935	
Parasite drag, with and without flaps	.78	5	.01	25	20	0	0	20	51.5	3500	118
			.02						53.4	3675	
			.03						56.2	3930	
			.04						60.5	4350	
	.78	5	.01	25	20	30	0	21	44.7	2740	118
			.02						46.4	2875	
			.03						48.5	3050	
			.04						50.8	3240	

In the above table, the load coefficient is that used at the N.A.C.A. tank to express the ratio of gross load to size of hull for a given form of hull and is defined as follows:

$$\text{Load coefficient, } C_{\Delta_0} = \frac{\Delta_0}{wb^3}$$

where

Δ_0 is gross load, lb.

w, specific weight of water, lb./cu. ft.

b, maximum beam of hull, ft.

The remaining parameters are defined as follows:

i_w , wing setting, deg. from base line of hull.

C_{Dp} , parasite drag coefficient, based on wing area and excluding the drag of the hull.

W/S, wing loading, lb. per sq. ft.

A_e , effective aspect ratio including ground effect.

δ_F , flap deflection, deg. from wing chord.

DISCUSSION OF RESULTS

Load coefficient.— Figure 3 shows a comparison of the total resistance curves using three load coefficients applied to the same hull lines, and with the flaps at 0° . The largest load coefficient, 1.1, corresponding to the smallest size of hull, obviously has too high hump resistance. The time and distance to stalling speed, using load coefficients of 0.5 and 0.78, vary but little. With the lighter loading, (larger hull), the time is slightly less and the distance is slightly more. Because of the small difference in performance for large differences in load coefficient, it is apparent that for this example the size of hull would probably be determined by other considerations such as spray, structural weight, or drag in flight. A load coefficient of 0.78 yields a reasonable size of hull and is, therefore, used for the remainder of the calculations.

With flaps down 30° (fig. 4), the variation with load coefficient is similar and the importance of size of hull on performance is not appreciably changed.

Wing setting.- For optimum performance, it would be desirable to vary the wing setting continuously with speed. In lieu of this, it is necessary to choose a compromise wing setting that will afford the best possible take-off. The wing setting is of importance since it influences the load on the water and the wing drag. Previous work on older designs of rather low aspect ratio (reference 5) has indicated that if the wing setting is selected for minimum total resistance at about 85 percent of the stalling speed, and trim for minimum water resistance is held throughout the take-off run, the take-off time and distance are about the optimum.

Figure 5 shows that this arbitrary method of selecting the wing setting is satisfactory for the present example.

In a flying boat with wings of high aspect ratio the increase in induced drag with increase of angle of attack is small; the L/D at large angles of attack (fig. 2) is such that it becomes profitable to take load off the water by increasing the wing setting. The optimum wing setting in this case is too large to be practicable; if used, the wings would be in the stalled attitude at around hump speed, although the hull would be at the trim corresponding to minimum water resistance.

Also, in flight the angle of the forebody keel of the hull will be at a negative value beyond the position for minimum air resistance. The wing setting must therefore be made less than that needed for optimum water performance.

For these reasons, 5° was assumed for the angle of wing setting for the first part of the investigation, whereas 9° would have given lower total resistance. An angle of wing setting of 9° was tried, however, in the aspect-ratio investigation because a high angle of wing setting was known to accentuate the effect of changes in aspect ratio.

Figure 6 shows the effect of angle of wing setting with flaps not deflected; figure 7 shows the effect with flaps deflected 30° . A comparison of the two figures

shows that with the use of flaps, the beneficial effect of the higher wing setting is reduced. A comparison of figures 8(a) and 8(b) shows that a change in angle of wing setting from 5° to 9° is almost as effective in unloading the hull as a change in deflection of the flap from 0° to 30° .

Trim.- The trim of the hull is one of the most important variables affecting the take-off performance of a seaplane. Resistance increases appreciably with departure from the trim corresponding to minimum water resistance. Hulls with a normal position of the center of gravity usually trim too high at the hump, where the elevator control is somewhat ineffective. Moving the center of gravity forward improves the trim, but often impairs the longitudinal stability.

Figure 9 shows the resistance curves of the hypothetical flying boat, using the trim for minimum water resistance and trims $1\text{-}1/2^\circ$ and 3° above and below this trim, with flaps set at 0° . The time and distance to stalling speed are increased by about 65 percent if the trim is 3° greater than the trim for minimum water resistance. The treatment of the speed range above stalling speed is discussed later. It is more desirable to be above rather than below the trim for minimum water resistance because an additional increment of air lift that lightens the load on the water is produced in the case of trimming up (see fig. 8(c)); this effect offsets to a certain extent the increase in water resistance accompanying the higher trim. An attempt to take off, keeping 3° below trim for minimum water resistance, would be impossible. Reference 5 shows a similar effect of trim on a smaller flying boat, with quite different hydrodynamic and aerodynamic characteristics.

The use of flaps does not greatly affect the magnitude of the increase in resistance at a given speed produced by trimming off the trim for minimum water resistance (see fig. 10) but the percentage increase is reduced because the total resistance has been increased by the additional profile drag of the flaps. A study of the effect of trim on total resistance, shown in figure 11, indicates that for high speeds the total resistance may be decreased when the angle of wing setting is too low, by using a trim greater than that for minimum water resistance. By staying $1/2^\circ$ or 1° above the trim for minimum water resistance, the total resistance is lower, begin-

ning at about 72 feet per second. The saving is small but definite up to the take-off speed. Too high a trim increases the total resistance to such an extent that the excess thrust may be insufficient to take the boat off the water.

In figure 11 the lines drawn between the curves of total resistance and thrust have a slope of Δ_0/g . The time in seconds is therefore given by the number of intercepts of the lines with the $R + D$ and thrust curves and the distance is the sum of the speeds at each second or intercept.

When the available thrust near take-off is limited, the necessity of maintaining a trim for minimum total resistance is accentuated. Figure 11 illustrates a method for determining the schedule of trims to be followed for a precision take-off, i.e., a take-off in which the hull is kept at an attitude giving the minimum total resistance. The envelope of the resistance curves in this figure (fig. 11) gives an optimum performance if the corresponding trim is maintained.

In figure 12 are shown the curve of trims for minimum water resistance in the high-speed range as obtained by computation and also the similar curve of trims, derived from figure 11, for precision take-off (optimum performance). It will be seen that the latter lies close to a trim of 7° for practically its entire length and it would appear that a constant trim of 7° through the high-speed range might be used as a substitute. Piloting technique beyond the stalling speed varies greatly and no definite analysis of the pull-off has been found.

Considering the three schedules of trims of figure 12 in turn it is seen that following the trim for minimum water resistance to fly-off the time is 77 seconds and the distance 6,900 feet. Following the trim of precision take-off exactly, the time is 61 seconds and the distance 4,700 feet. Holding the trim constant at 7° to fly-off, the time is 63 seconds and the distance 4,900 feet. This emphasizes the fact that in the example the take-off in the high-speed range consists substantially of holding the trim about constant at 7° throughout, without a pull-up.

Figure 13 shows the effect of increasing the trim too rapidly or too soon. In this figure it is assumed

that the trim changes at rate of 1.5° per second beginning at 118 feet per second, the stalling speed. A sharp peak occurs in the total resistance curve which, if the pull-off is started too soon or is too rapid, might be sufficiently high to prevent take-off. For this particular design of flying boat, a rapid pull-off should not be started below 123 feet per second.

This method for determining precision trim can be applied to any design for which aerodynamic and hydrodynamic performance data are available. Time may be saved by computing the $R + D$ for several fixed trims of the hull and using the envelopes of these curves as suggested in reference 6.

Deflection of flaps.- The effect on take-off of several constant deflections of the flaps is shown in figure 14 for a wing loading of 25 pounds per square foot and a load coefficient of 0.78. With the 15° deflection the total resistance is slightly greater than for 0° deflection. However, the take-off occurs at a lower speed due to the faster unloading. Increasing the deflection of the flaps to 30° increases the total resistance by a larger percent in the planing region and reduces the take-off by a smaller percent. The advantage of the faster unloading is decreased because of the greater aerodynamic drag with a 30° deflection. Out to the stalling speed the time and distance are about the same with the flaps deflected at 15° or 30° . The take-off examples of reference 7, using a smaller hypothetical boat, show the same trends.

Figure 15 shows the effect of flaps for a wing loading of 35 pounds per square foot, and illustrates the increased importance of flaps for the purpose of increasing the lift and decreasing the load on the water when the wing loading is increased.

A study of the resistance curves, using several constant deflections of the flaps, suggests that take-off could be improved by deflecting the flaps just prior to stalling speed, in that way taking advantage of the lower stalling speed without paying the penalty of increased resistance during the remainder of the take-off. Upon investigation, it was found that it was entirely practicable to deflect flaps of existing large four-engine airplanes of late design from 0° to 30° in about 5 seconds.

Figure 16 shows the theoretical gain in take-off performance made possible by delayed deflection of the flaps.

The scale of the figure is chosen to give an enlarged view of the high-speed portions of the $R + D$ curves in figure 14. It is assumed that the flaps are kept at 0° up to a speed of about 80 feet per second, which is attained 32 seconds after the start; then the flaps are deflected at the conservative rate of 30° in 20 seconds or $1\frac{1}{2}^\circ$ per second. The dotted line represents the resulting resistance, and was obtained by making a first approximation of the speed for a given elapsed time and deflection of the flaps, then obtaining the wing lift, load on the water, and resistance at the trim for minimum water resistance. Running through a second approximation using the speeds obtained from the first approximation gave the required accuracy. This gives a time of 52 seconds and a distance of 3,700 feet for the take-off. This may be compared to a precision take-off without flaps; the time is decreased by about 15 percent and the distance by about 25 percent when the delayed action of the flaps was used.

If the flaps are deflected from 0° to 30° in 6 seconds, a much shorter take-off is obtained. The total resistance curve for such a take-off is shown by the short dash line in figure 16. Its departure from the $\delta_F = 0^\circ$ curve is practically negligible out to the point where the $\delta_F = 30^\circ$ curve crosses the $\delta_F = 0^\circ$ curve. It then follows the $\delta_F = 30^\circ$ curve to take-off speed.

Wing loading.— A wing loading of 25 pounds per square foot was assumed for most of the investigations because it permitted enough excess thrust for take-off in a reasonable length and time using variations that increased the total resistance considerably. Existing designs of 100,000-pound flying boats have wing loadings of 30 pounds per square foot or more and contemplate the use of flaps for taking off and landing. To make the present investigation cover the trend to greater wing loadings with increase in size, a wing loading of 35 pounds per square foot was investigated in connection with deflection of the flaps. Increasing the wing loading normally increases the parasite drag coefficient. However, this change is small and was neglected in this investigation. A study of figures 14 and 15 will show that the high-speed resistance is increased appreciably by the higher wing loading. Moreover, the thrust curve has dropped until the excess thrust is small. The use of flaps before stalling speed would reduce seriously the amount of excess thrust. If flaps are not used, the

get-away occurs at such a high speed that the $R + D$ curve almost touches the thrust curve.

As wing loadings become greater, more emphasis will be placed on the importance of low water resistance at high speeds. Methods of assisting unloading of the hull, such as higher angles of wing setting and the use of flaps for pull-off, will offset to a certain extent the effect of the higher wing loadings.

Aspect ratio.- Figure 17 shows the effect of varying the assumed geometrical aspect ratio while the wing is at a constant height above the water. The flaps were not deflected and the angle of wing setting was 5° . At high speeds the larger aspect ratios give a small but definite improvement.

Figure 18 shows the increased importance of aspect ratio when an angle of wing setting of 9° is used. The reason for this is that the greatest divergence in the drag curves of the various aspect ratios (see fig. 2) occurs at angles of attack above 12° , where the lift and the induced drag become appreciable.

The same kind of reasoning applies to the use of high aspect ratios with deflected flaps. The lift coefficient becomes much higher, induced drag is increased, and the beneficial effect of higher aspect ratios in reducing the induced drag is therefore increased.

Higher aspect ratios increase the optimum angle of wing setting, but unless hulls are specifically designed to have low air drag when cruising with the hull down by the bow, the higher wing settings could not be profitably used.

Parasite drag.- Figure 19 shows the effect of parasite drag, without the use of flaps. Parasite drag becomes important at stalling speed and above. In this high-speed range the thrust curve may have dropped sufficiently to make the magnitude of the parasite drag an important factor in the performance.

When the flaps are deflected to 30° (see fig. 20), the drag of the wings is increased, and the parasite drag represents a smaller percent of the total. Since the take-off speed has decreased, and the available thrust at take-off is therefore greater, the resistance added by the parasite drag is less critical.

CONCLUSIONS

The following conclusions apply particularly to a design having the characteristics assumed for this investigation, but they may be useful in predicting changes in performance produced by the same variable in other designs.

1. Load coefficient:

- a. The take-off performance is not particularly sensitive to change in load coefficient resulting from change in the size of hull for a given form. The upper limit in load coefficient may be determined by the magnitude of the resistance at hump speed.
- b. When flaps are used, the effect of load coefficient is similar to what it is without flaps.

2. Wing setting:

- a. With increase in aspect ratio, the angle of wing setting for optimum take-off becomes greater than it is feasible to use.
- b. The loss in take-off performance resulting from the use of wing settings lower than optimum is less when flaps are used.

3. Trim:

- a. Up to the stalling speed, deviations of more than $1-1/2^\circ$ above or 1° below the trim for minimum water resistance result in a large increase in total resistance and consequently in time and length of take-off.
- b. The above limits also apply when flaps are used.
- c. Trims above that for minimum water resistance have less adverse effect on take-off performance than trims below that for minimum water resistance.
- d. Above the stalling speed, the trim for minimum

total resistance becomes greater than that for minimum water resistance. Too high a trim, however, results in a sharp increase in total resistance. The best procedure for taking off consists essentially in holding a constant trim somewhat above that for minimum water resistance rather than in sharply increasing the trim.

4. Deflection of flaps:

- a. Flaps increase the total resistance at planing speeds but decrease the get-away speed. The net effect of their use with high wing loadings is to improve take-off performance.
- b. The favorable effect of the flaps increases with wing loading.
- c. The best take-off performance is obtained by deflecting the flaps quickly at high speeds, thus taking advantage of the lower get-away speed without increasing the total resistance in the planing range.

5. Wing loading:

- a. Increase in wing loading impairs the take-off performance and increases the importance of low water resistance at high speeds.
- b. The use of flaps, large wing settings, and high aspect ratio is favorable in offsetting the disadvantageous effect of high wing loading.

6. Aspect ratio:

- a. Increase in aspect ratio definitely improves take-off performance. The improvement is most notable at effective aspect ratios below 20; above 20 the improvement is small.
- b. The improvement is greater for high angles of wing setting than for low angles.

7. Parasite drag:

- a. The effect of parasite drag is most marked at high speeds and hence is important when high wing loadings are used.
- b. The use of flaps lessens the effect of parasite drag on take-off performance.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 28, 1939.

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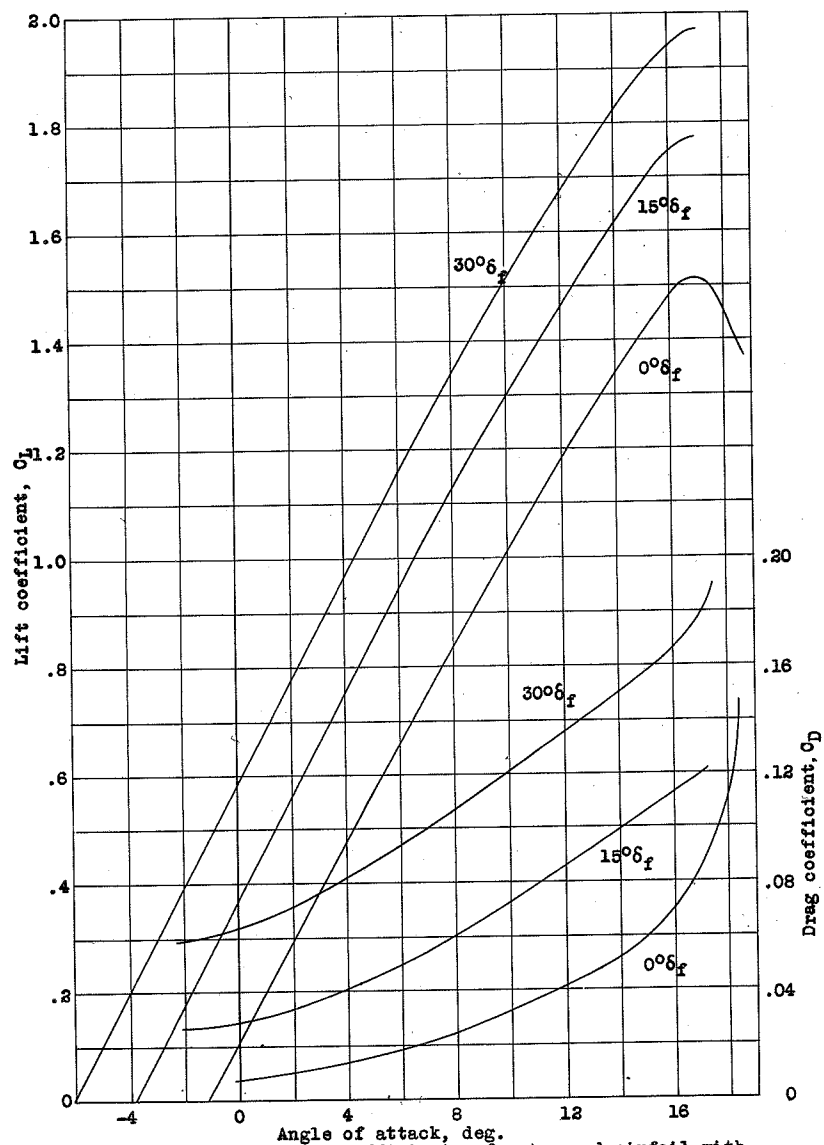


Figure 1.- Lift and drag coefficients of a tapered airfoil with various flap deflections. $A_e=20$, ground effect included.

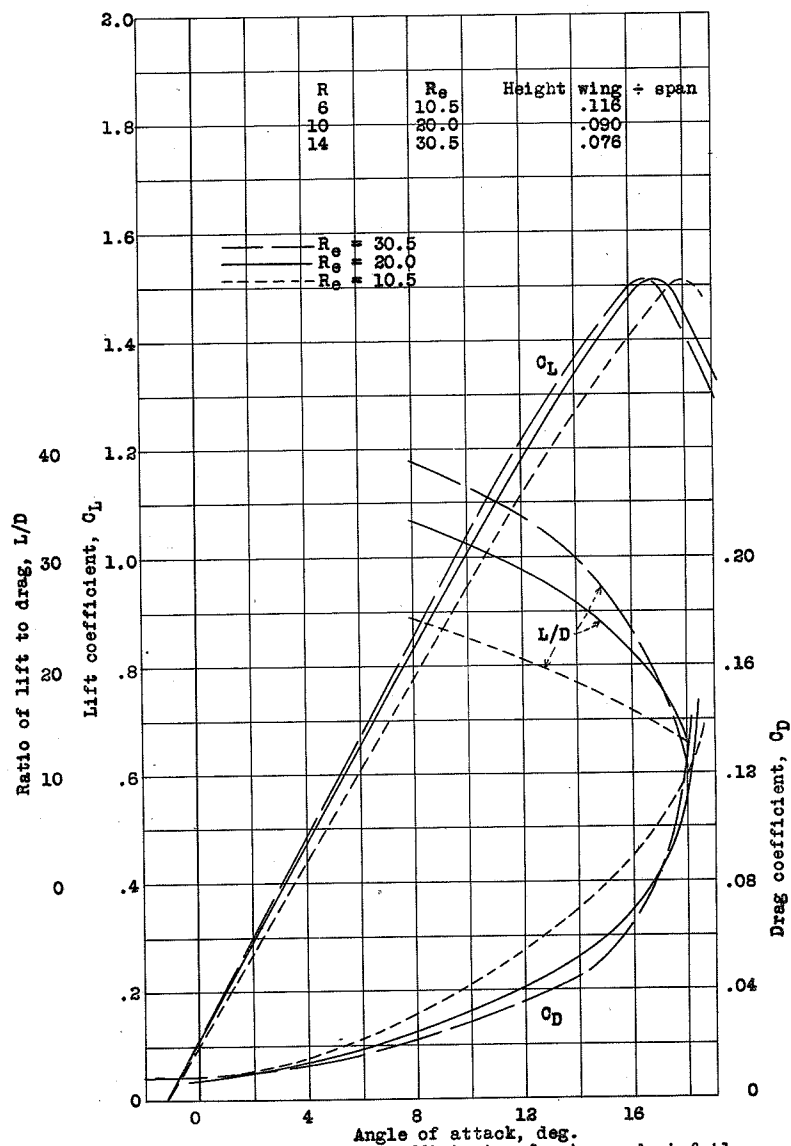


Figure 2.- Lift and drag coefficients of a tapered airfoil, of various aspect ratios, including ground effect.

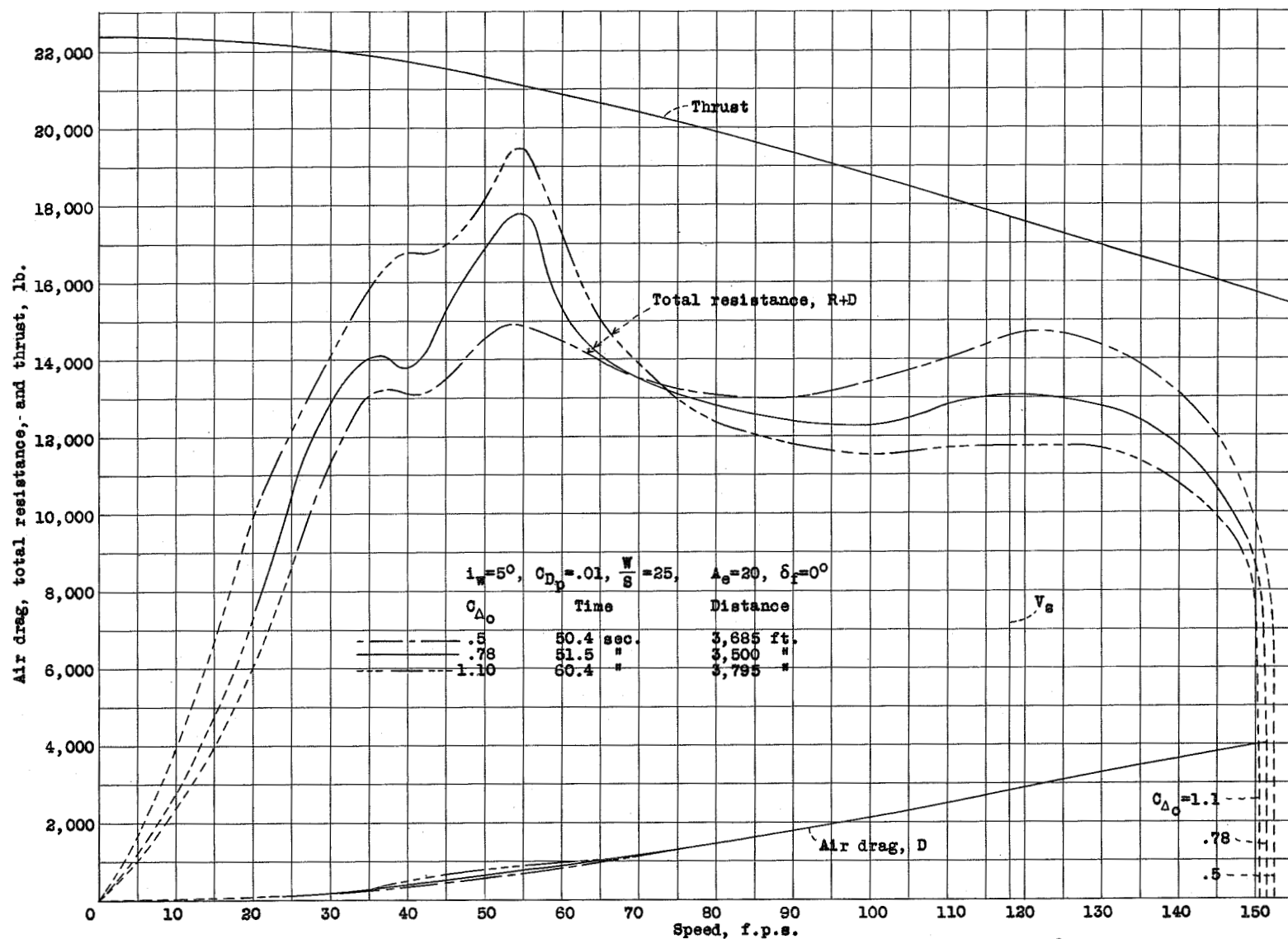


Figure 3.- Effect of load coefficient, $C_{\Delta o}$, on take off, with flaps set at 0° .

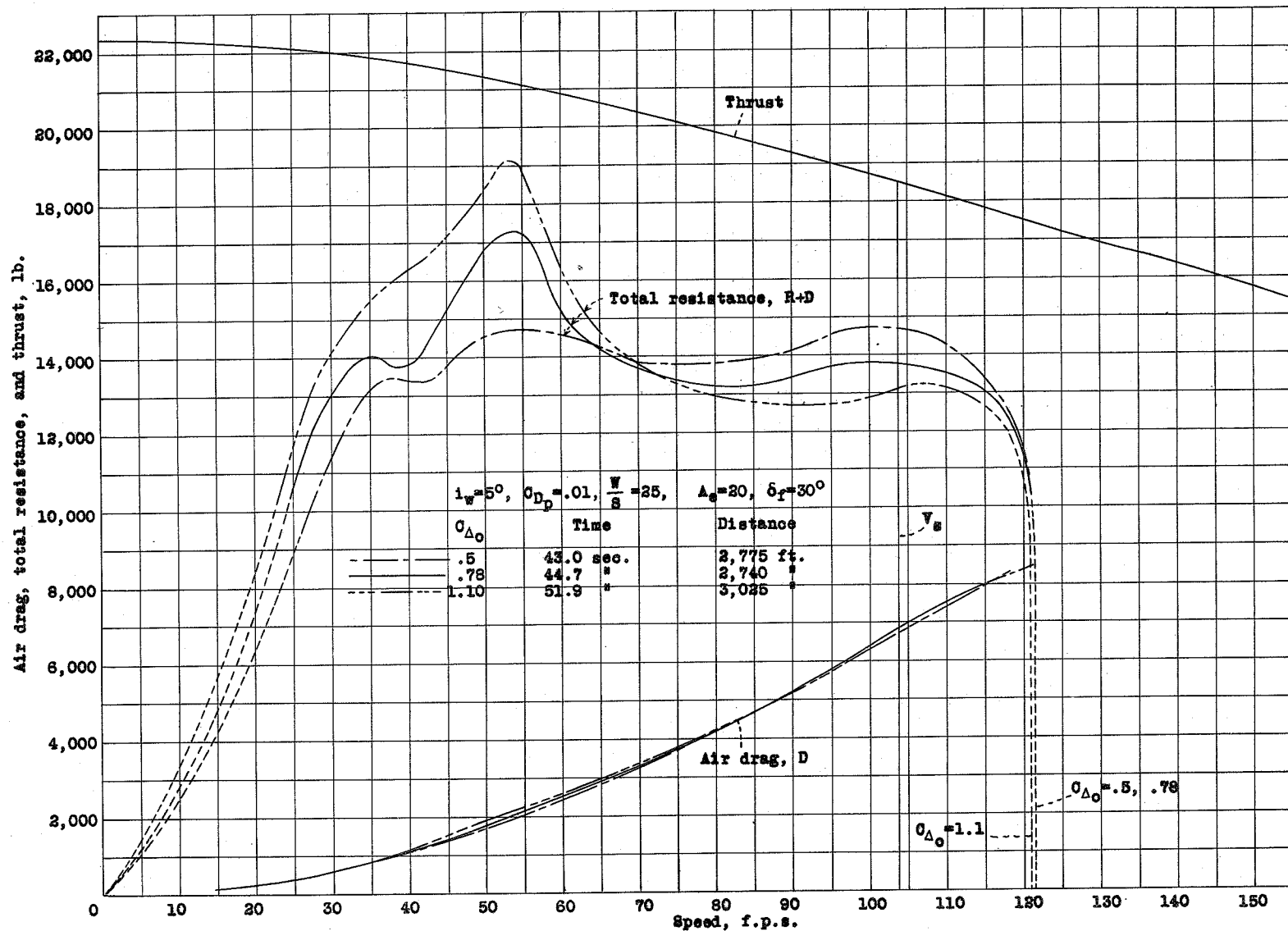


Figure 4.- Effect of load coefficient, C_{Δ_0} , on take off, with flaps set at 30° .

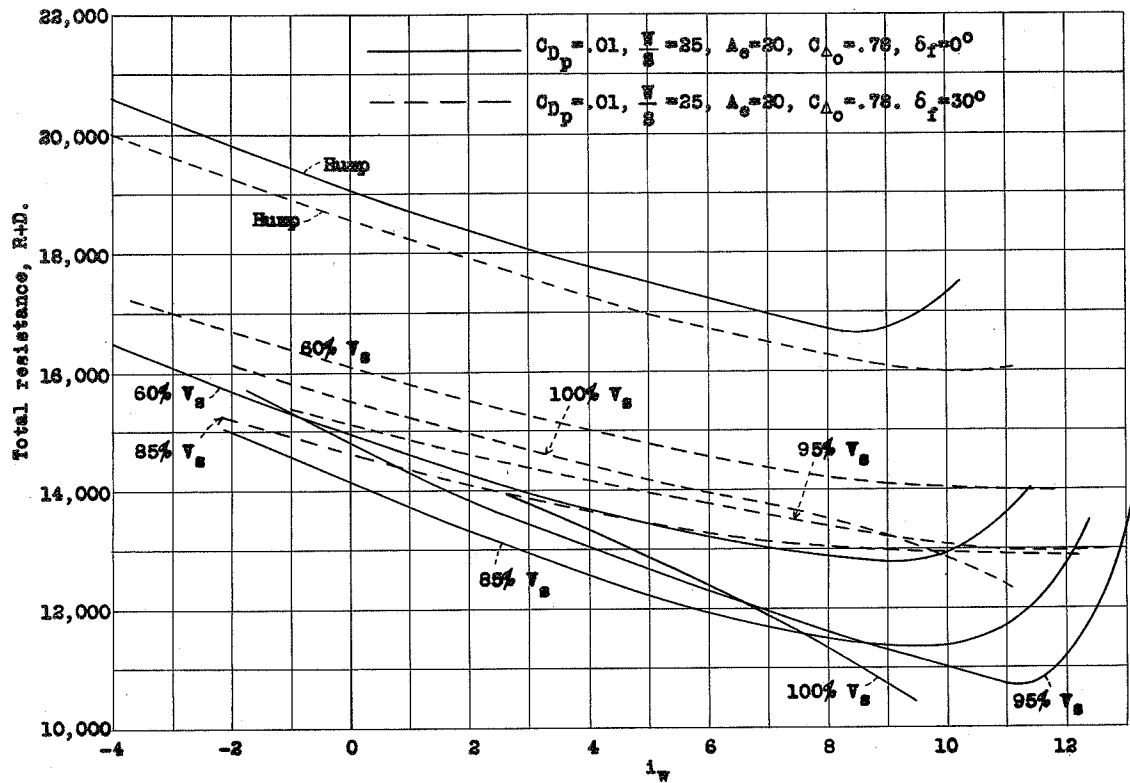


Figure 5.- Variation of R+D with angle of wing setting.

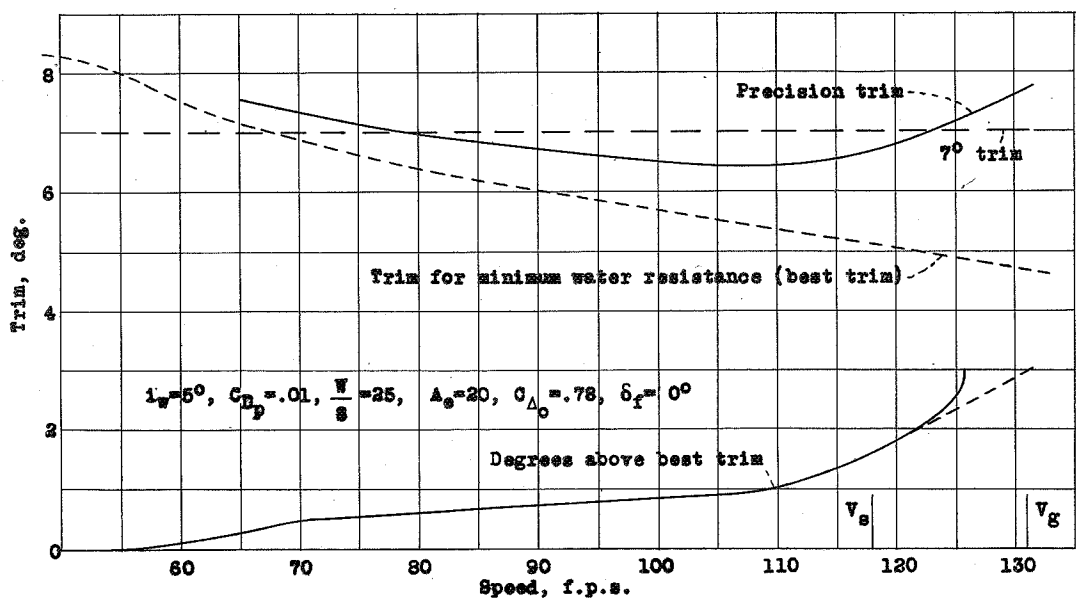


Figure 12.- Trim schedule at high speeds for a precision take off.

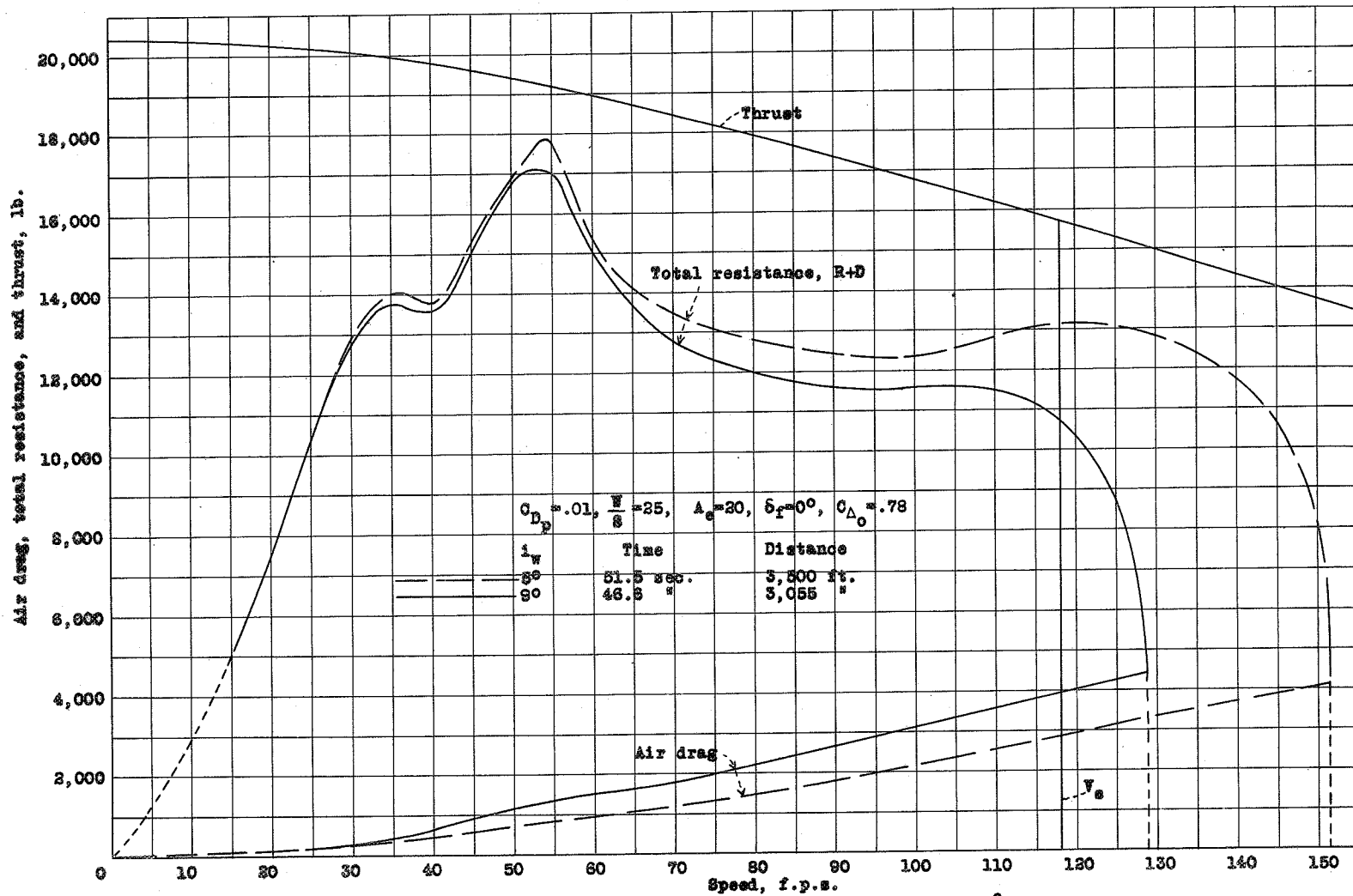


Figure 6.- Effect of wing setting, i_w , on take off, $\delta_f = 0^\circ$.

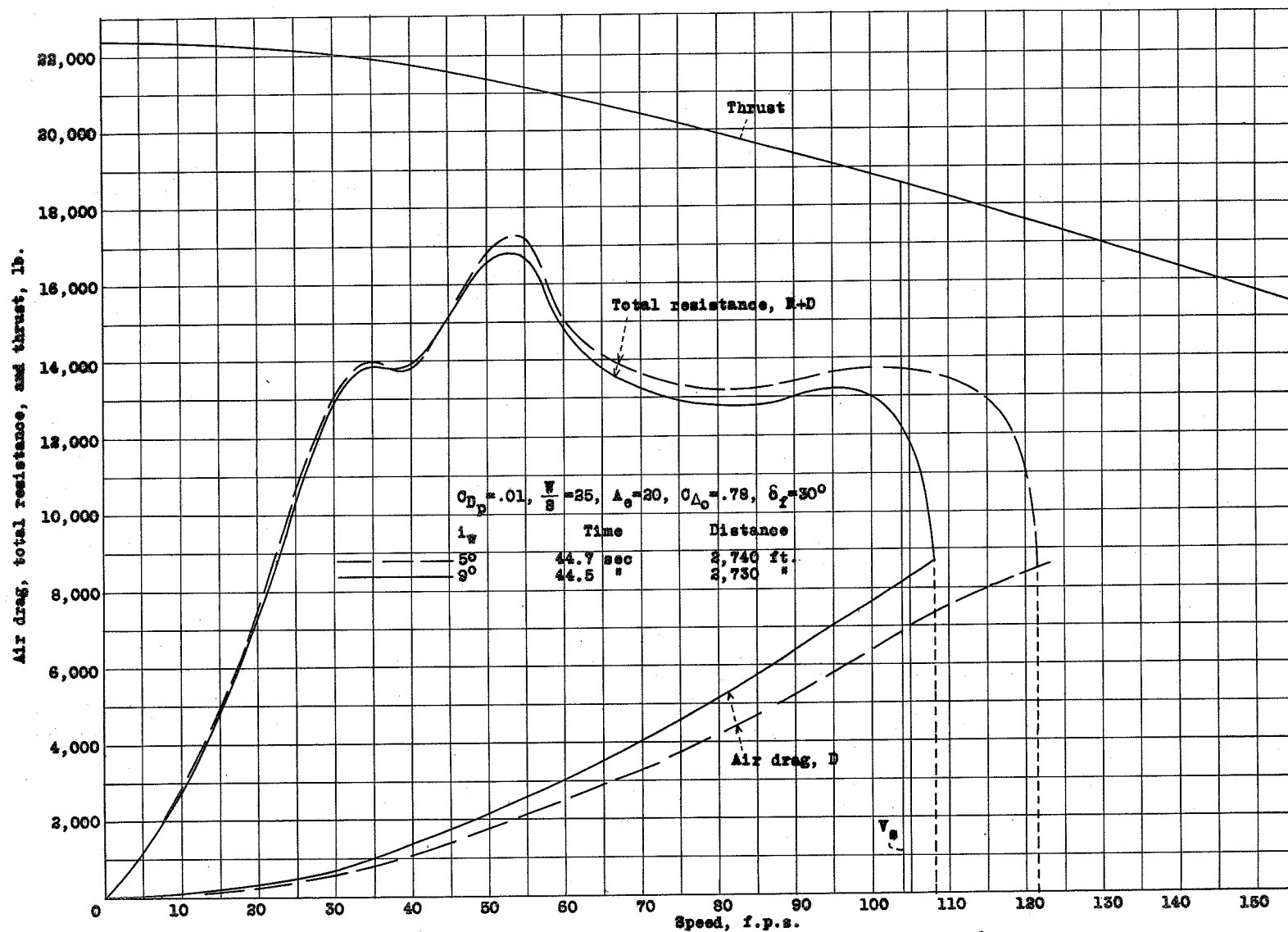


Figure 7.- Effect of wing setting, i_w , on take off, $\delta_f = 30^\circ$.

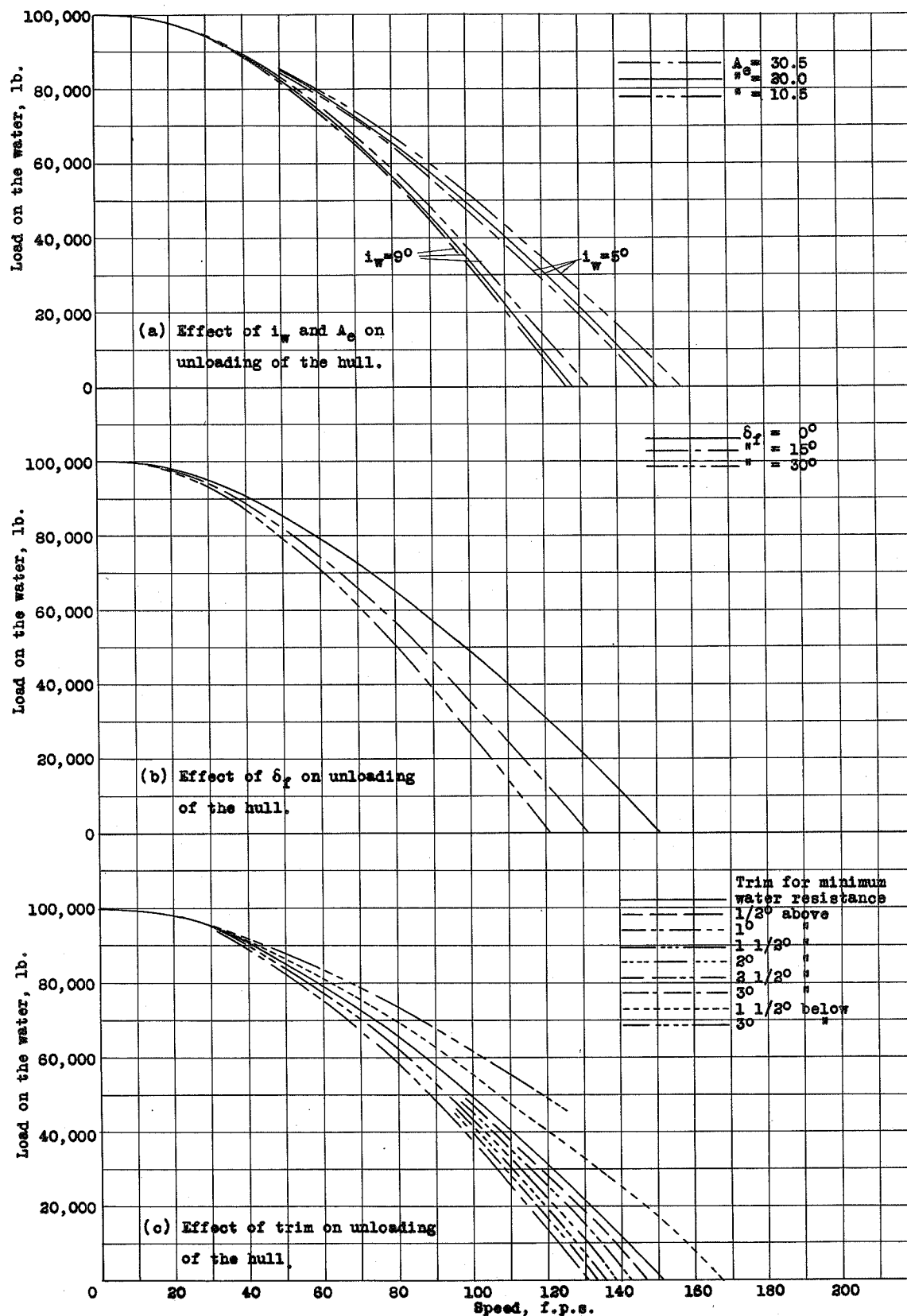


Figure 8.- Effect of various factors on unloading of the hull.

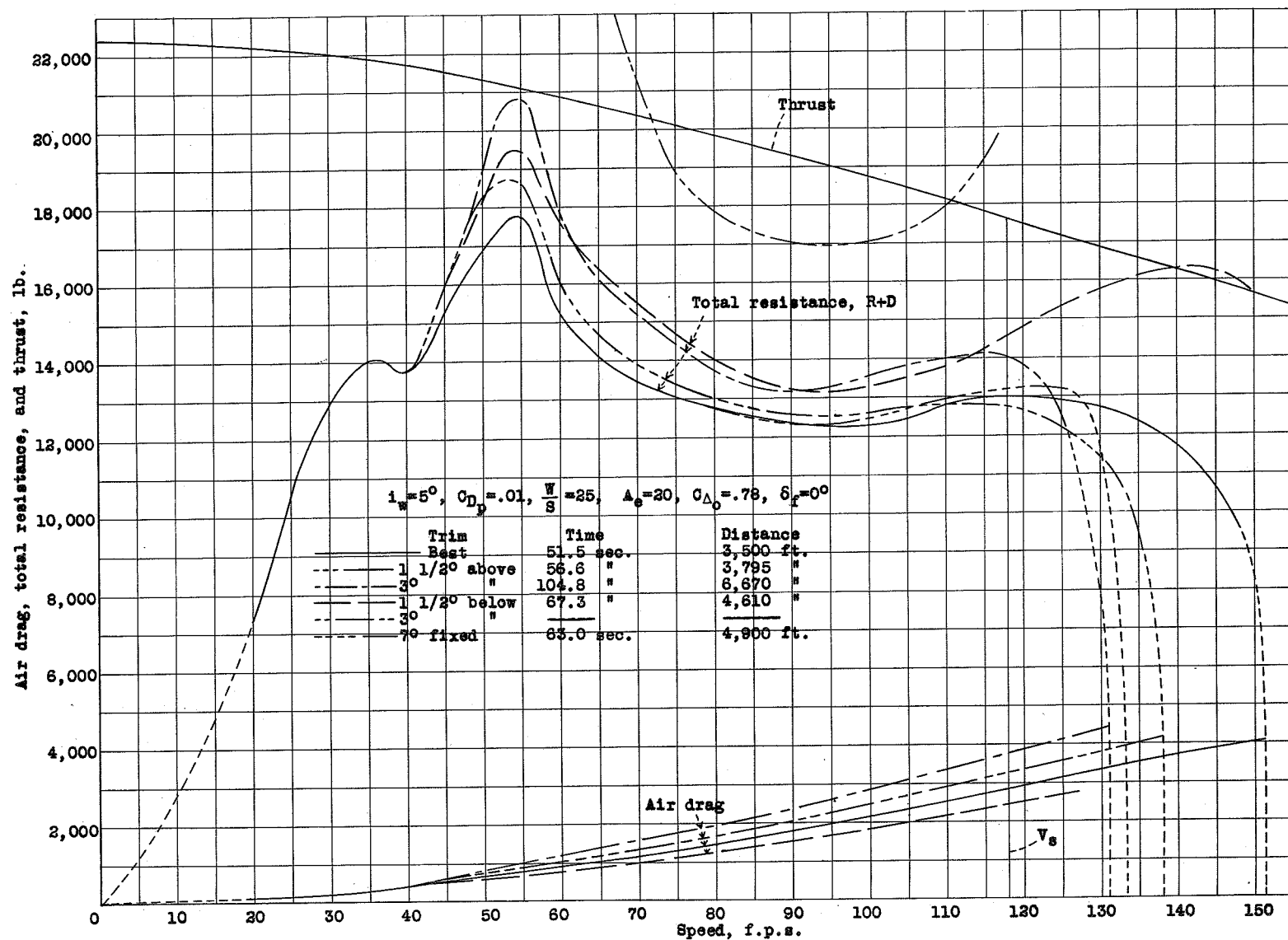


Figure 9.- Effect of trim on take off with flaps set at 0°.

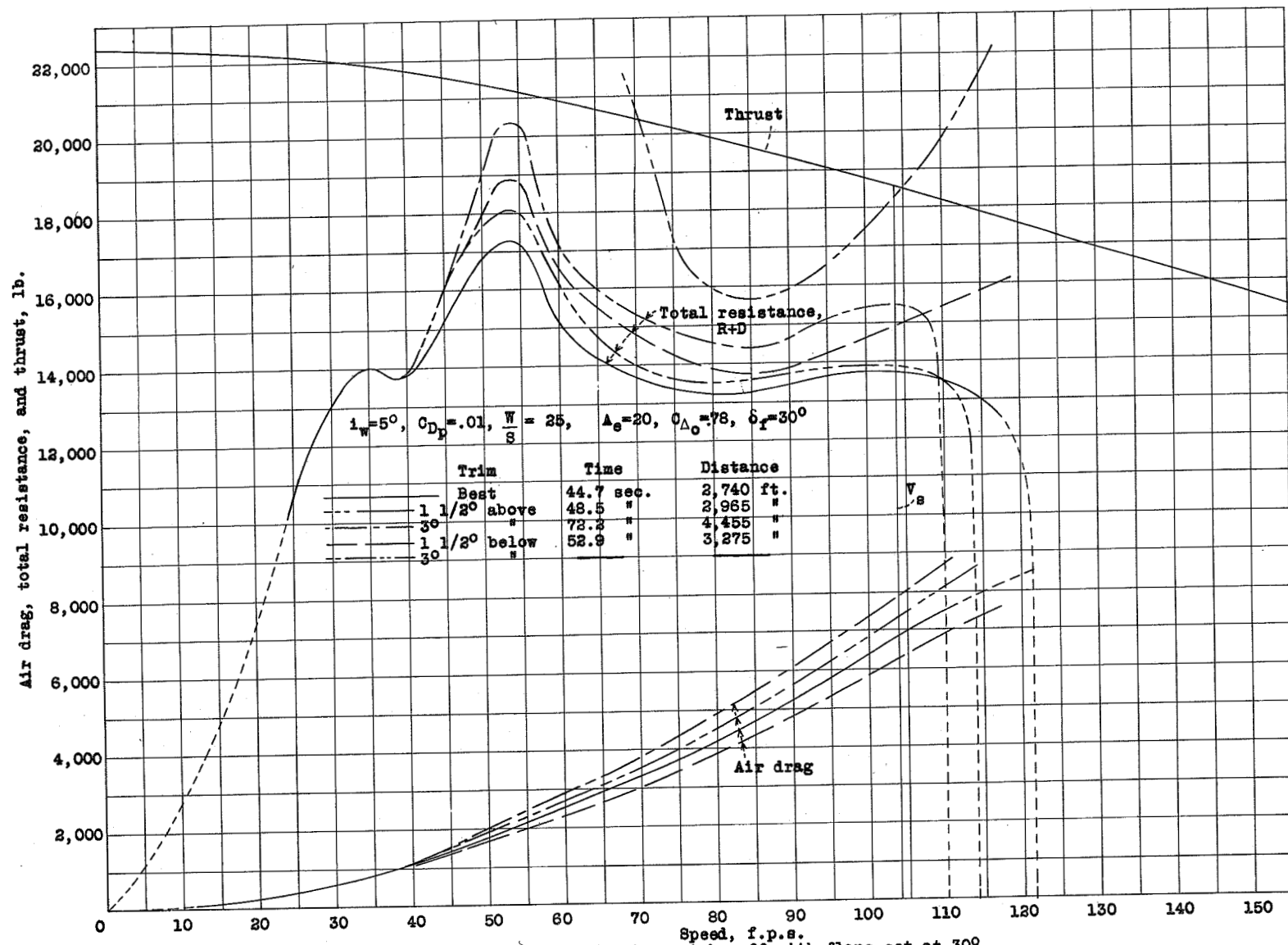


Figure 10.- Effect of trim on take off with flaps set at 30° .

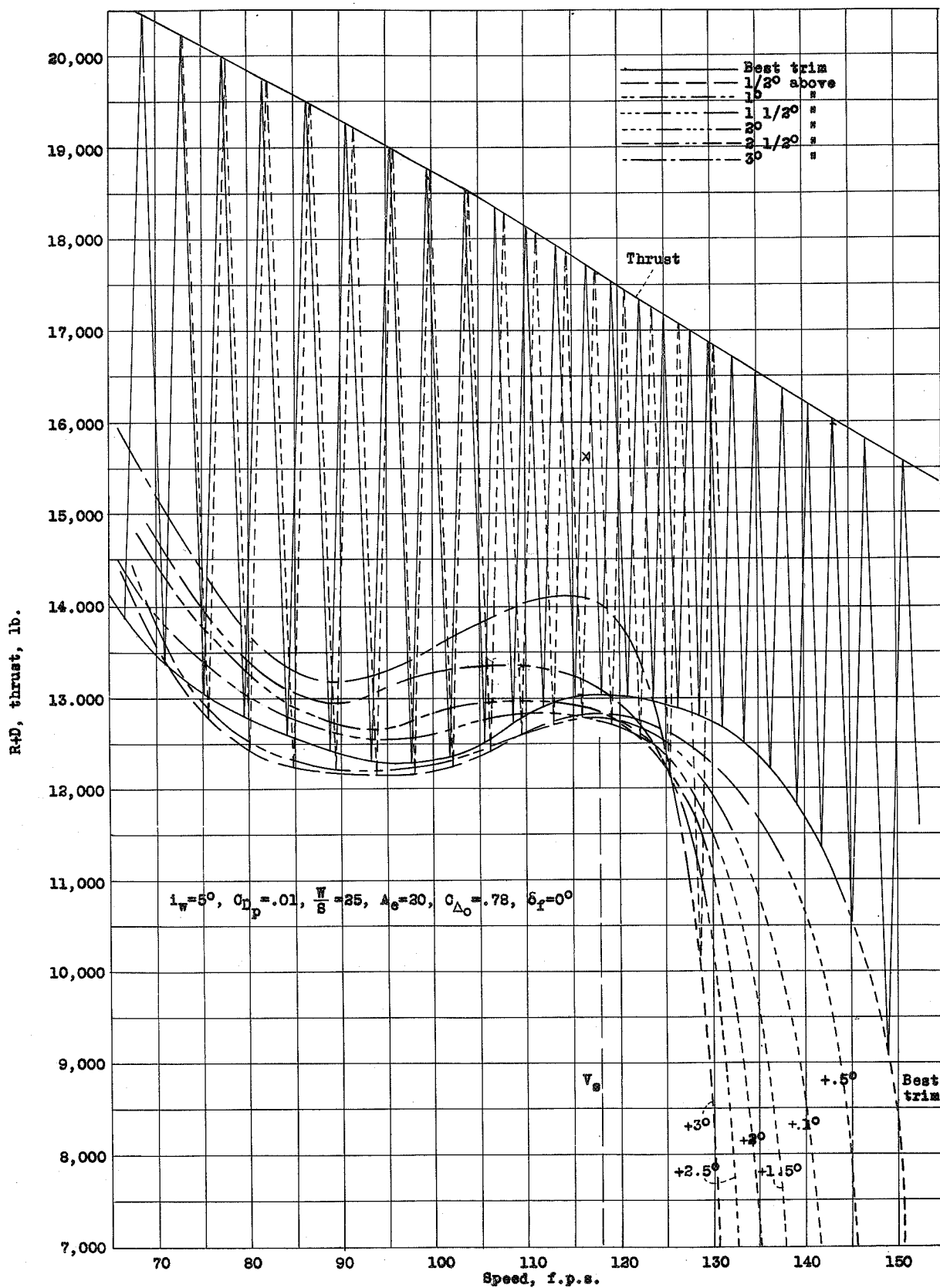


Figure 11.- Effect of trim at high speeds.

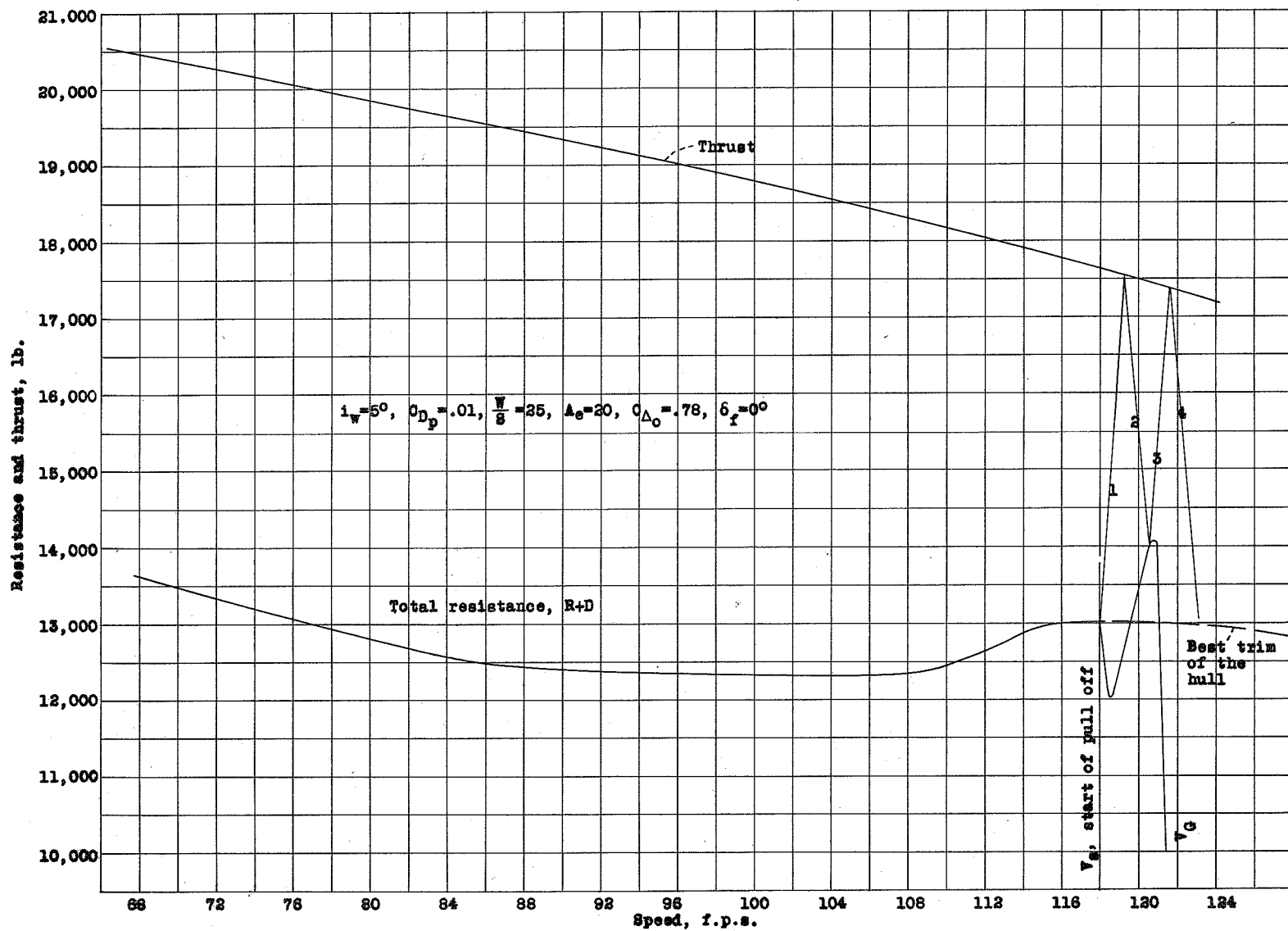


Figure 13.- Effect of pulling up at rate of 1.5° per second.

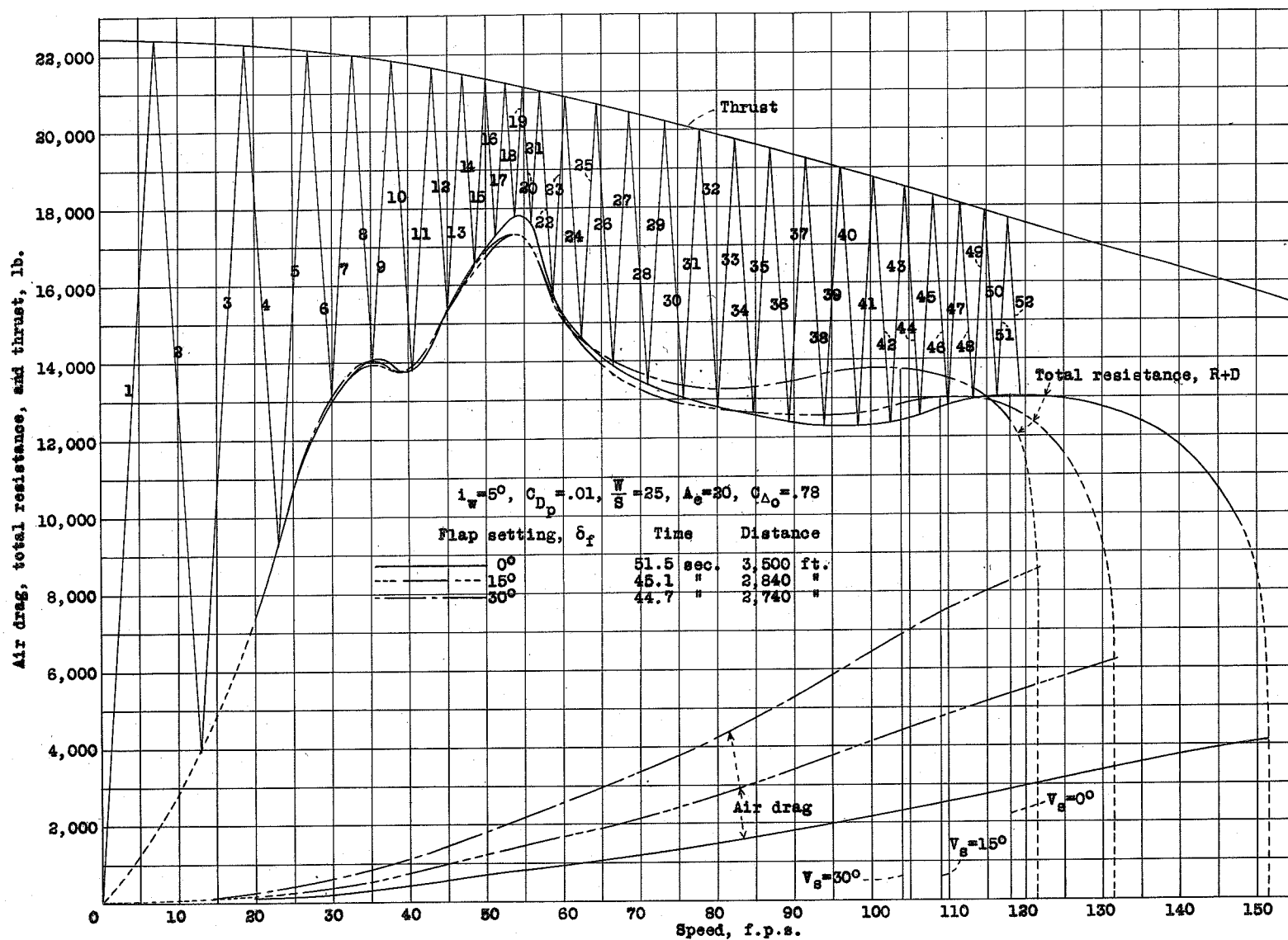


Figure 14.- Effect of flaps on take-off, for wing loading of 25.

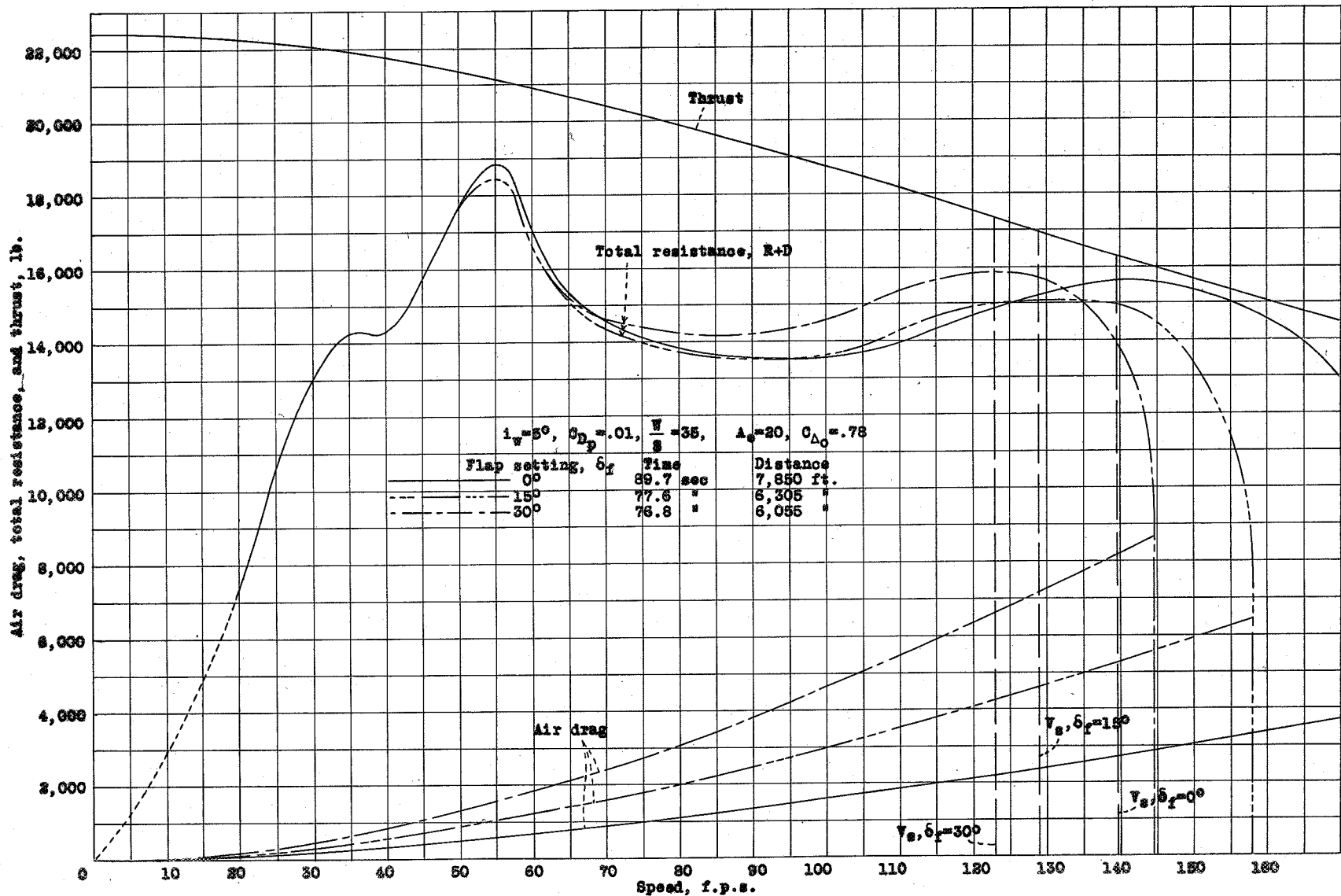


Figure 15.- Effect of flaps on take-off, for wing loading of 35.

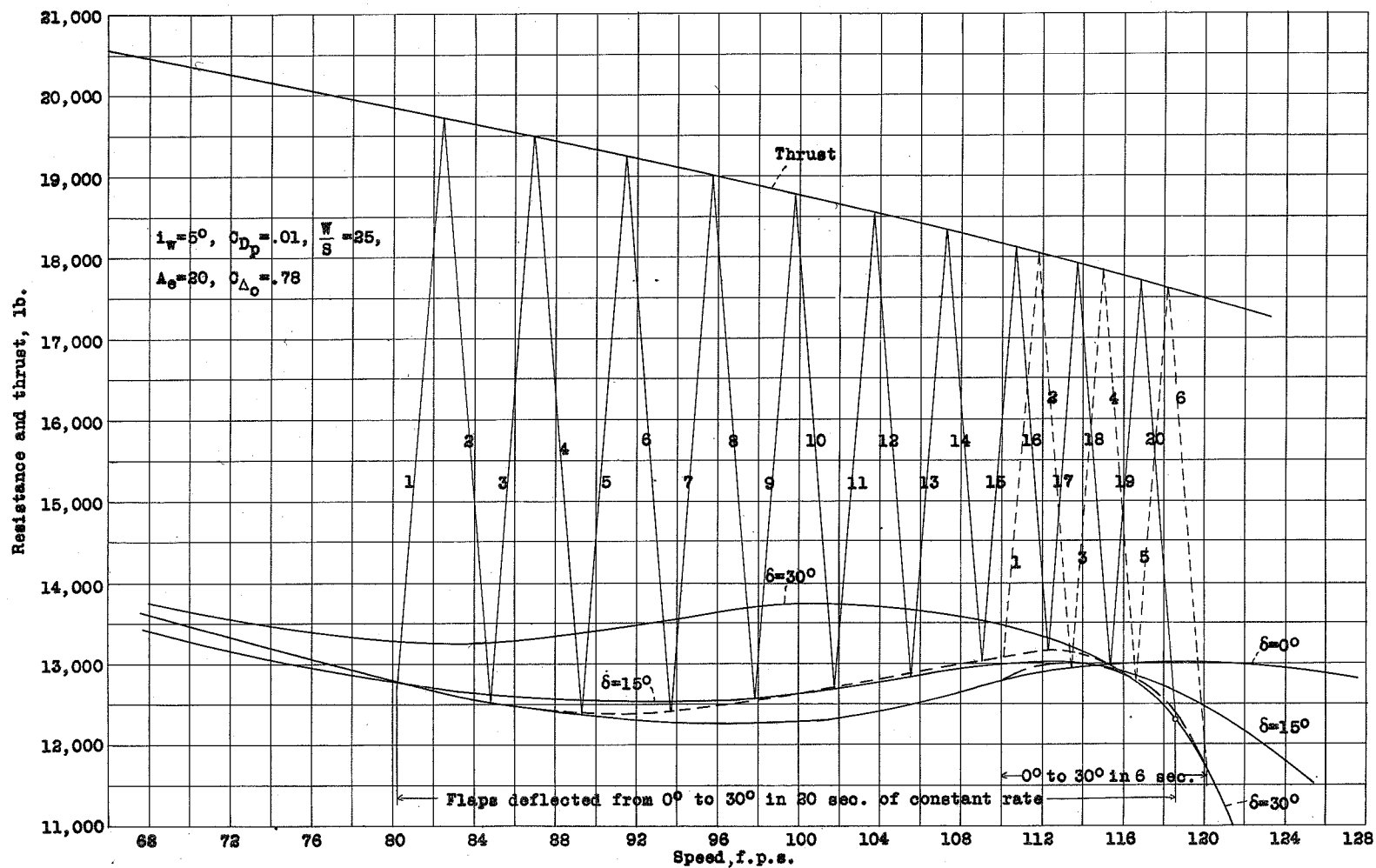


Figure 16.- Pull off, deflecting flap while keeping hull at best trim.

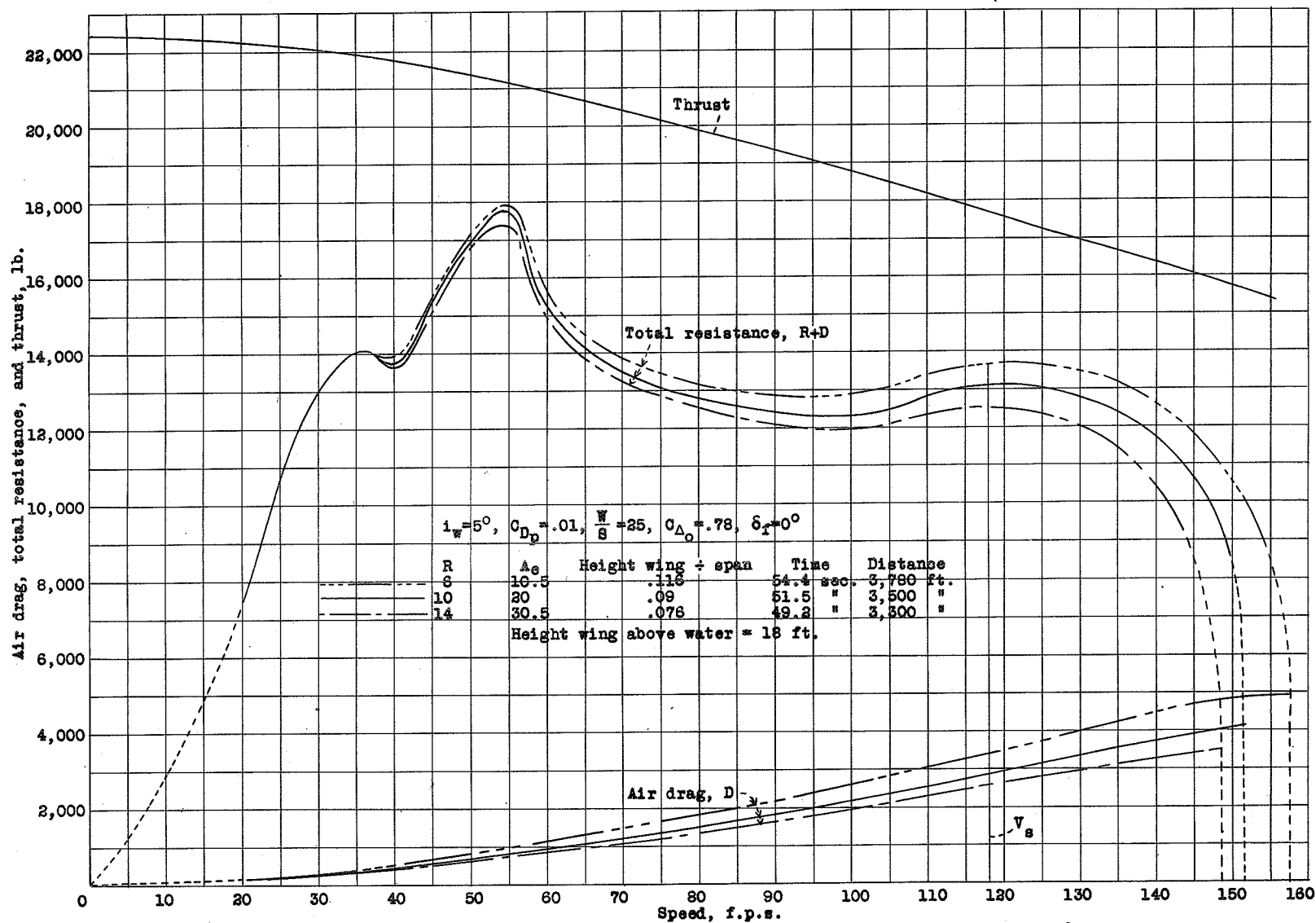


Figure 17.- Ground effect, using various spans at a constant height above the water, $i_w = 5^\circ$.

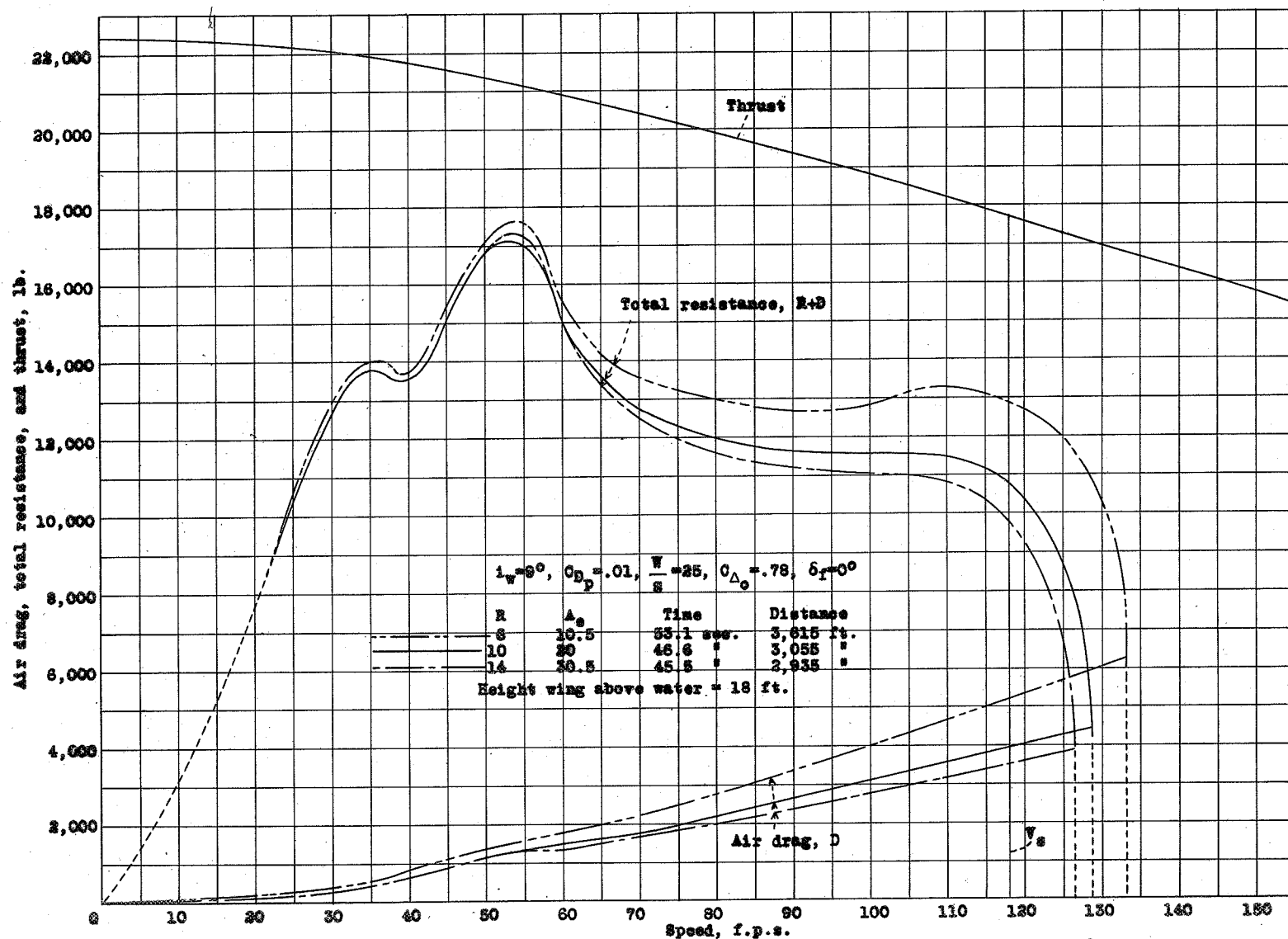


Figure 18.- Ground effect, using various spans at a constant height above the water, $i_w = 0^\circ$.

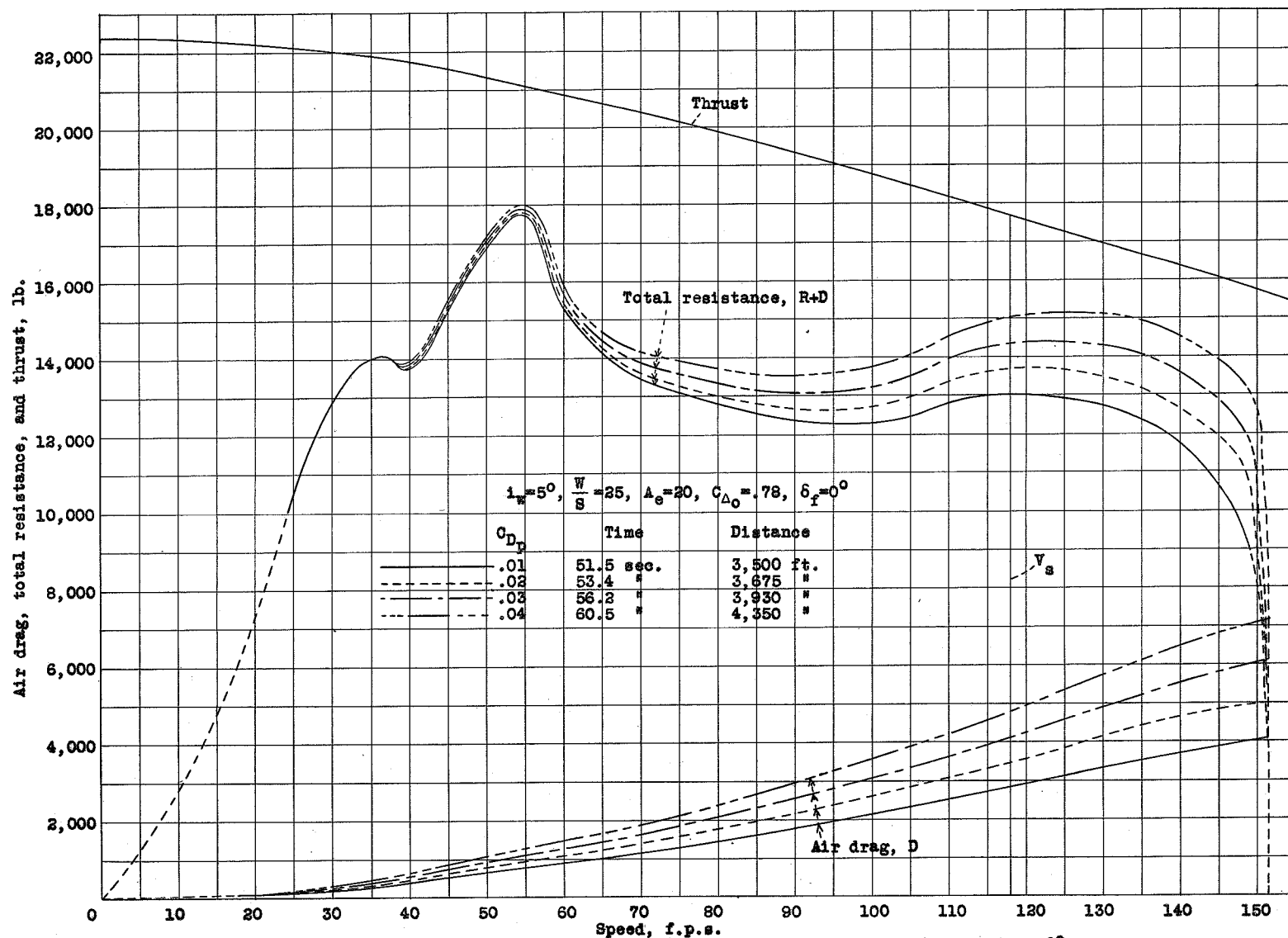


Figure 19.- Effect of parasite drag coefficient, C_{D_p} , on take off, with flaps set at 0° .

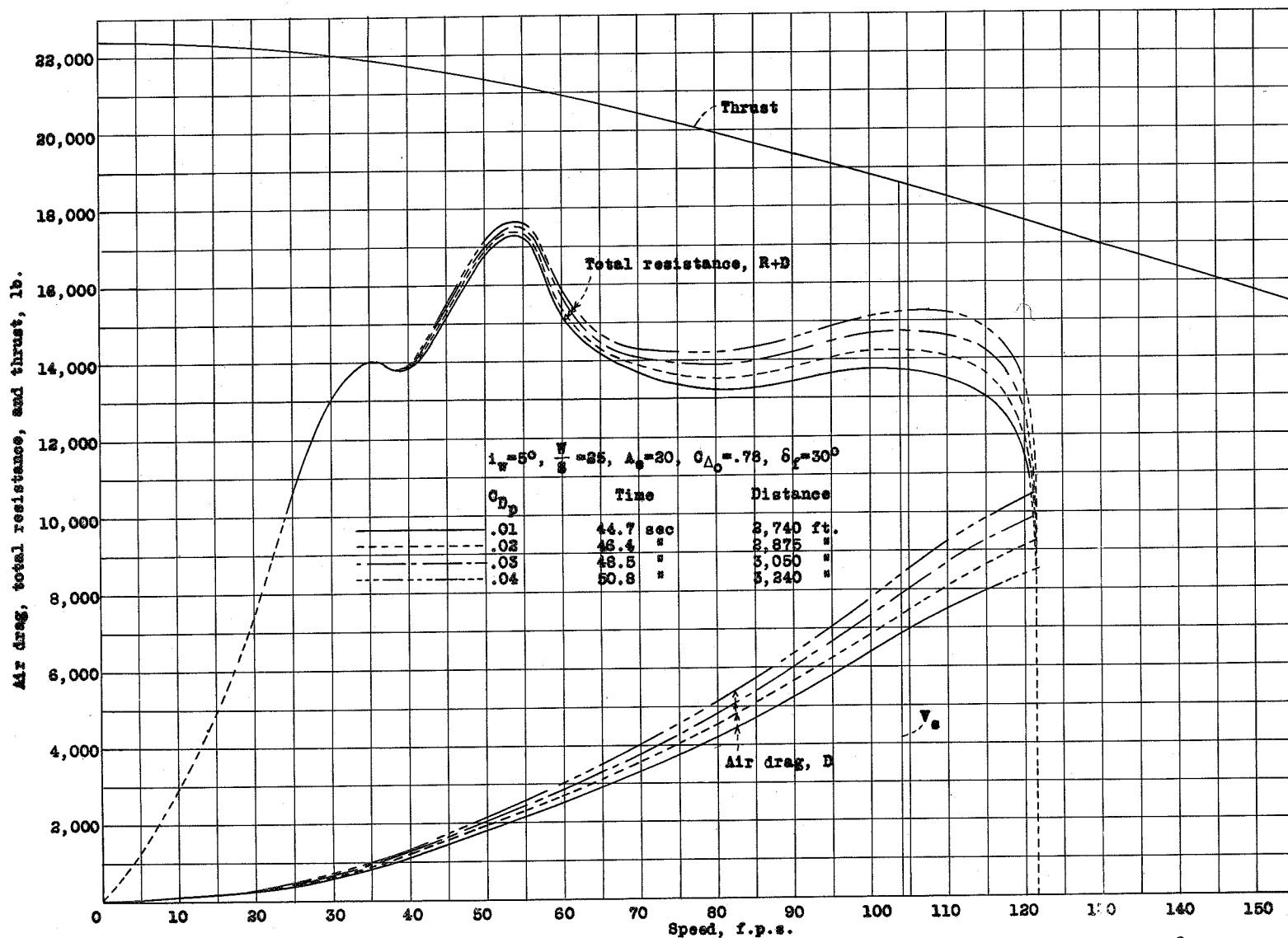


Figure 20.- Effect of parasite drag coefficient, C_{Dp} , on take off, with flaps set at 30° .